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# Revisiting the capture of Mercury into its 3:2 spin-orbit resonance

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**Abstract.** We simulate the despinning of Mercury, with or without a fluid core, and with a frequency-dependent tidal model employed. The tidal model incorporates the viscoelastic (Maxwell) rebound at low frequencies and a predominantly inelastic (Andrade) creep at higher frequencies. It is combined with a statistically relevant set of histories of Mercury’s eccentricity. The tidal model has a dramatic influence on the behaviour of spin histories near spin-orbit resonances. The probabilities of capture into high-order resonances are greatly enhanced. Exploring several scenarios, we conclude that the present 3:2 spin state was achieved by entrapment of an initially prograde cold Mercury when its age was less than 20 Myr, i.e., well before differentiation.

**Keywords.** celestial mechanics, planets and satellites: individual (Mercury)

## 1. Previous studies

In the literature hitherto, three scenarios of Mercury’s entrapment have been discussed.

(a) *A prograde rigid Mercury.* The probability of capture into the 3:2 spin-orbit state is  $\approx 7\%$ , with a constant eccentricity  $\approx 0.206$ , see Goldreich & Peale (1966). The probability increases to  $\approx 55\%$  due to multiple crossings induced by secular variations of the eccentricity, see Correia & Laskar (2004).

(b) *A prograde Mercury with a liquid core.* Within this scenario, Mercury was more likely to be trapped into the 2:1 resonance than into the 3:2 one, as demonstrated by Peale & Boss (1977), Correia & Laskar (2009).

(c) *A Mercury once synchronised.* Wieczorek *et al.* (2012) argued that the allegedly asymmetric distribution of impact craters was the signature of a past synchronous rotation destabilised later by an impact.

All these scenarios rely on the CTL (*Constant Time Lag*) tidal model, which cannot be applied to terrestrial planets of considerable viscosities. Among the mathematical consequences of that model is a *stable state of pseudosynchronous rotation* on which the previous studies are based. We revisit these scenarios, using a physics-based tidal model.

## 2. A more realistic tidal model

At low obliquities, the polar tidal torque reads as (Noyelles *et al.* (2014))

$$\tau_{\text{tide}} \approx \frac{3}{2} \frac{GM_{\star}^2}{a} \left( \frac{R}{a} \right)^5 \sum_{j,q=-\infty}^{\infty} G_{20q}(e) G_{20j}(e) k_2 \sin \epsilon_2 \cos [(q-j)\mathcal{M}]. \quad (2.1)$$

$\mathcal{M}$  and  $n \equiv \dot{\mathcal{M}}$  are the mean anomaly and mean motion;  $\theta$  and  $\dot{\theta}$  are the rotational angle and spin rate of the planet;  $k_2 \sin \epsilon_2$  is a function the Fourier mode  $\omega_{2m0q} \approx (2 + q)n - m\dot{\theta}$ . Its shape is determined by the planet's self-gravitation and rheology. Viscoelastic (Maxwell) at low frequencies, the rheology comprises both viscoelastic and inelastic reaction (Andrade creep) at higher frequencies (Efroimsky(2012)).

Kink-shaped, the quality function  $k_2(\omega_{2m0q}) \sin \epsilon_2(\omega_{2m0q})$  goes continuously through zero in the resonance  $\omega_{2m0q} = 0$ . With all terms expressed as functions of  $\dot{\theta}$ , the series (2.1) is a superposition of kinks. Employment of this torque radically changes the entrapment probabilities and excludes pseudosynchronism, see Makarov & Efroimsky(2013).

### 3. Scenario 1: A prograde rigid Mercury

As soon as our tidal model is used, Mercury almost always gets trapped into the 3:2 resonance *on the first crossing*. Moreover, the absence of a stable pseudosynchronous rotation makes several crossings impossible. So, if Mercury is not trapped into a high-order resonance, it falls into the synchronous one. A hot Mercury (with a short Maxwell time  $\tau_M$ ) is more likely to fall into the 2:1 resonance than into the current 3:2.

### 4. Scenario 2: A prograde Mercury with a core

We also considered a differentiated Mercury with core-mantle friction, following Goldreich & Peale (1967). When our tidal model is used, the 2:1 resonance is certain for the current eccentricity (0.206). Only a past low eccentricity or a collision disrupting the 2:1 resonance (Correia & Laskar (2012)) could have made the current configuration possible.

### 5. Scenario 3: A once synchronous Mercury

The distribution of craters, according to the MESSENGER data (Fassett *et al.* (2012)), suggests an East-West asymmetry consistent with a past synchronous rotation. However, the absence of pseudosynchronous stable rotation requires the impact to be energetic enough to make Mercury reach the 3:2 resonance. This would leave a crater larger than 600 km, while the use of the CTL model would require only a crater of 300 km. For a detailed critical analysis of this scenario, see Noyelles *et al.* (2014).

## 6. Conclusion

Within the Scenario 1 of an initially prograde cold Mercury, the 3:2 resonance is the likeliest end state. The capture takes place in less than 20 Myr, well before differentiation.

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